

ANALYSIS OF FACTORS CONCERNED IN MAINTAINING ENERGY BALANCE FOR DRESSED MEN IN EXTREME COLD; EFFECTS OF ACTIVITY ON THE PROTECTIVE VALUE AND COMFORT OF AN ARCTIC UNIFORM¹

H. S. BELDING,² H. D. RUSSELL, R. C. DARLING³ AND G. E. FOLK³

From the Laboratory of Industrial Physiology (formerly Fatigue Laboratory), Harvard Graduate School of Business Administration, Boston, Mass.

Received for publication November 29, 1946

It has been shown that a large fraction of the sweat produced by heavily clothed men during work in the cold remains in the clothing and is relatively ineffective for skin cooling (Belding, Russell, Darling and Folk, 1947). For example, when a man walked at 3.5 miles per hour up a 6.5 per cent grade at 0°F. sweat was secreted at a rate of about 500 grams per hour, of which 400 were held in the clothing. It was calculated that the net sweat effective for evaporative cooling of the skin was 230 grams per hour, which included the 100 grams that escaped to the environment, plus 130 grams, the calculated effective equivalent of the 400 grams taken up by the clothing. However, despite this low efficiency of cooling per gram of sweat it was concluded that sweating could be a quantitatively important mechanism for heat dissipation; in this example efficiency of cooling by sweat was only 46 per cent, yet 23 per cent of the energy produced by the man was dissipated by this avenue.

One purpose of the present investigation was to determine at various levels of activity not only what fraction of the total energy produced was lost through sweating, but also the part played by the other avenues of energy loss, namely, by convection and radiation from the skin, by warming the inspired air and vaporizing the water in the lungs, and by performing the work of lifting the body. Such information could then be used for evaluating the thermal protection provided by heavy clothing and for revealing factors which may limit its usefulness.

Another purpose was to assess the part played by a suit of Arctic clothing as a thermal barrier under various circumstances of use and to evolve a method of predicting under what conditions this clothing would provide thermal comfort.

Most earlier studies of thermal exchanges of clothed men have been concerned with effects of light clothing on heat exchanges during moderate activity or while resting. One stimulus for those studies came from the air-conditioning

¹ This work was started under a contract recommended by the Committee on Medical Research, between the Office of Scientific Research and Development and the President and Fellows of Harvard College; it was finished under a contract recommended by the Committee on Quartermaster Problems, between the National Academy of Sciences and the President and Fellows of Harvard College.

² Present address: Climatic Research Laboratory, Lawrence, Massachusetts

³ Present address: College of Physicians and Surgeons, Columbia University, New York, New York

engineers, who wanted to know the range of temperatures and humidities which were comfortable for persons dressed in conventional clothing. Yaglou et al. (1927, 1941) and Houghton, Teague, Miller and Yant (1929) have been active in providing practical answers to this question. Perhaps the most complete analysis of energy exchanges of lightly clothed as compared with nude men has been made at the Pierce Laboratory (Gagge, Winslow and Herrington, 1938; Winslow, Herrington and Gagge, 1938, a, b; and Winslow, Gagge and Herrington, 1939). Using their method of partitional calorimetry, they determined the influence of wall and air temperatures and humidity on storage of body heat and on exchanges of heat due to radiation, convection, and evaporation of sweat.

Gagge, Burton and Bazett (1941) indicated that when the wearer is in a "steady state" the heat flow through his clothing by radiation and convection (H_{cl}) may be derived by subtracting evaporative heat loss via the lungs and skin from metabolic energy production; they further showed that if skin and air temperatures are known the insulation provided by clothing may readily be computed. They suggested the "Clo" as a suitable unit of insulation⁴. In those units

$$I_{clo} = \frac{3.09(T_s - T_a)}{H_{cl}} - I_a \quad (1)$$

where I_{clo} is the insulation in Clo units, T_s and T_a are skin and air temperatures in degrees Fahrenheit, I_a is the insulation in Clo units of the layer of air surrounding the clothing, and H_{cl} is the heat lost from the body by convection and radiation in Cals./m²/hr. We wish to point out that this method of calculation is strictly applicable only when the insulation over all parts of the body is the same. When insulation varies from region to region, as with the Arctic uniform used in this study, the insulation values obtained by the above method may be in error by 10 per cent or more; however, the method has the advantage of being practical and of yielding a useful approximation of insulation value.

These principles and the new unit of insulation were used in wartime for the evaluation of uniforms and sleeping gear designed for military use in cold weather (Burton, 1941; Belding, Darling, Griffin, Robinson and Turrell, 1945). They are employed here, with modifications, to partition the avenues of energy loss of men engaged in various levels of activity while dressed in Arctic clothing as well as to determine the effects of activity on the insulation provided by clothing and to predict the temperature levels for comfort at various activity levels.

⁴ One Clo is the protection provided by an ordinary business suit. It will provide comfort for a man while sitting quietly in a room at 70°F. with air movement at 20 ft./min. and humidity less than 50 per cent. Under these comfortable conditions skin temperature, T_s , averages 92°F., insulation of the air, I_a , is 0.78 Clo, and metabolic energy production is about 50 Cals./m²/hr., of which about 24 per cent, or 12 Cals./m²/hr., are lost by evaporation of moisture from the skin and lungs, leaving 38 Cals./m²/hr. as the heat lost by radiation and convection, H_{cl} . Then, substituting in equation (1):

$$I_{clo} = \frac{3.09(92 - 70)}{38} - 0.78 = 1.0$$

METHODS. Two subjects, G. S. and J. S., were studied intensively using procedures described by Belding et al. (1947) for determination of sweating, moisture uptake of the clothing, net effective sweating, energy production, pulmonary ventilation, average skin temperature, rectal temperature, and comfort. From these data the factors entering into the energy balance equation were derived. The equation applicable here was

$$M + D = (E_i + A) + W + E_s + H_{cl}, \quad (2)$$

where for convenience all values were expressed in Calories per square meter of body surface per hour.

The factors signified by these symbols are defined and were calculated as follows (cf. Belding, Darling, Griffin, Robinson and Turrell, 1945):

- M = metabolism, and is considered to represent total energy production, both heat and external work. This was calculated from oxygen consumption as previously described (Belding et al., 1947).
- D = heat loss, or debt of the body mass ($-D$ = heat gain). It was derived (method of Burton, 1945a) by weighting change in mean skin temperature one-third and in rectal temperature two-thirds to determine the change in average body temperature; this value for the change ($^{\circ}\text{C}.$) was then multiplied by the assumed specific heat (0.83) and by body weight (Kgm.) to determine the debt in Calories.
- $E_i + A$ = heat loss as a result of evaporation of water from the lungs (E_i) and in warming the inspired air (A). Values were obtained by using the nomogram prepared by Belding et al. (1945); applicable assumptions were that the inspired and expired air were saturated with vapor at $0^{\circ}\text{F}.$ and $91.5^{\circ}\text{F}.$ respectively (cf. Christie and Loomis, 1933); $A = 0.65 E_i$ when ambient temperature is $0^{\circ}\text{F}.$
- W = external work of lifting the body in uphill walking experiments. It was calculated by multiplying kilograms of weight lifted (subject + clothing) by meters of height climbed and by 427 to convert work in kilogram-meters to equivalent Calories.
- E_s = heat loss in vaporization of sweat. This was calculated by multiplying the net effective sweat values obtained as described by Belding et al. (1947) by 0.58 Calories per gram.
- H_{cl} = heat loss through the clothing by radiation and convection (and possibly to a very limited extent by conduction). This was determined by solving equation (2) with H_{cl} as the only unknown.

All experiments reported here were conducted at $0^{\circ}\text{F}.$, with the subjects clothed in the Arctic uniform described in the preceding paper. All experiments lasted for two hours, except one; this was a one-hour run at 6 miles per hour.

RESULTS AND DISCUSSION. *Energy exchanges as a function of activity.* Values obtained for the factors entering into energy balance at various levels of activity are given in table 1. The levels of activity represented ranged from sitting quietly (metabolism at 53 Cals./m²/hr.) to climbing a 12 per cent grade at 3.5 miles per hour (metabolism at 424 Cals./m²/hr.). Data on pulmonary ventilation, rectal temperature changes and net effective sweat, necessary for determination of some of these factors have been presented in table 4 of Belding et al. (1947).

We have data enough on these two subjects to decide in what respects their

responses were similar and different. Both men performed 11 of the 16 activities represented in table 1, activities ranging in intensity from sitting quietly to

TABLE 1
Factors in energy balance when performing various grades of activity in an Arctic Uniform at 0°F.

(For key to symbols see text; values are in Cals./m²/hr.)

NO. EXPS.	ACTIVITY OR SPEED	GRADE	M	D*†	E _t + A*	W	F _s *	H _d	I _{do}	FINAL T _s
Subject G. S. (Ht. 176 cm.; wt. 62 kgm.; surface area 1.76 m ²)										
	m.p.h.	%								°F.
1	Sit		53	28	7	0	-3	77	3.1	84
1	Stand		63	45	9	0	11	88	2.6	79
1	1.29	0	110	17	12	0	6	109	2.1	85
1	1.80	0	123	13	13	0	10	113	2.0	86
1	2.25	0	146	10	17	0	7	132	1.6	83
1	3.00	0	167	18	18	0	26	141	1.5	85
3	3.50	0	208	7	21	0	22	172	1.2	85
1	3.50	2.75	238	0	25	15	32	166	1.3	89
1	3.50	3.25	241	-2	24	17	42	156	1.4	88
1	3.50	3.75	264	0	24	20	38	182	1.1	89
1	3.50	4.50	260	-3	24	24	49	160	1.3	89
7	3.50	6.50	316	-8	32	34	72	170	1.2	89
2	3.50	9.75	364	-13	35	52	94	170	1.2	91
1	3.50	12.00	424	-16	41	64	120	183	1.1	90
Subject J. S. (Ht. 178 cm.; wt. 73 kgm.; surface area 1.90 m ²)										
1	Sit		59	45	11	0	7	86	2.7	83
1	Stand		72	38	18	0	6	86	2.7	85
1	1.29	0	112	33	18	0	6	121	1.8	86
1	1.80	0	137	21	21	0	6	131	1.7	87
1	2.25	0	145	19	23	0	4	137	1.6	87
1	3.00	0	173	8	29	0	6	146	1.5	86
3	3.50	0	189	-3	32	0	11	143	1.5	88
1	3.50	2.50	216	4	35	14	10	161	1.3	88
1	3.50	3.00	229	3	39	17	17	159	1.3	88
1	3.50	3.25	228	3	36	18	26	151	1.4	89
1	3.50	4.50	262	-2	37	25	35	163	1.3	89
7	3.50	6.50	304	-11	48	36	49	160	1.3	89
2	3.50	9.75	371	-21	58	55	72	165	1.3	91

* Data necessary for deriving these values are presented in the paper by Belding et al. (1947).

† In calculating heat debt an initial mean skin temperature of 90°F. was assumed.

climbing a 9.75 per cent grade. The average values obtained on each man in the eleven experiments appear in table 2.

Since for both men *a*, average energy production was the same on a unit surface area basis; *b*, average final rectal temperature was the same; *c*, average final skin temperature differed by only 1.5°F., and *d*, average heat debt of the body

mass differed by less than 2 Cals./m²/hr., it may be concluded that the temperature-regulating centers of both men accomplished about the same adjustment of energy loss to energy production at any one level of activity. In other words the "setting" of the temperature-regulating center, while differing from activity to activity, was at corresponding levels of activity the same for both men.

Total energy loss was about the same for both men at any one activity, and two components of total energy loss were about the same, namely, heat loss through the clothing (H_{cl}) and energy loss as work (W). However, losses through respiration ($E_r + A$) and through sweating (E_s) were quite different for the two men. Subject G. S. had a volume of ventilation which averaged 36 per cent less than J. S. at each activity, and accordingly his loss of heat by this avenue averaged 10.8 Cals./m²/hr. less than that of J. S. G. S. compensated for this by sweating more, with the result that he lost 9.6 Cals./m²/hr. more by evaporation

TABLE 2
Average values obtained in the eleven experiments performed by both subjects

FACTOR IN ENERGY BALANCE	G. S.	J. S.	DIFF.	BODY TEMPERATURE	G. S.	J. S.	DIFF.
	Cals./m ² /hr.	Cals./m ² /hr.	Cals./m ² /hr.		°F.	°F.	°F.
M	186.5	186.5	0.0	Final skin T.	85.4	83.9	+1.5
D	10.1	11.8	-1.7	Initial rectal T.	98.8	98.4	+0.4
$E_r + A$	19.3	30.1	-10.8	Final rectal T.	99.4	99.4	0.0
W^*	31.8	33.5	-1.7				
E_s	30.3	20.7	+9.6				
H_{cl}	135.3	135.4	-0.1				

* In 4 uphill walking experiments only.

of sweat than did J. S. It is now evident that the extra sweat secreted by G. S. was secreted in an amount appropriate to compensate for his smaller heat loss via respiration (cf. Belding et al., 1947).

Figure 1, prepared from the data in table 1, shows graphically the interrelations of the factors concerned in energy balance at various levels of energy production. The figure indicates:

a. That for each man heat lost in respiration was a straight line function of metabolism approximately described as follows:

$$\text{for G. S.: } E_r + A = 0.10M \quad \text{for J. S.: } E_r + A = 0.16M$$

b. That the external work done was proportional to total energy production when grade of climb was varied between 0 and 12 per cent at a speed of 3.5 miles per hour; the energy cost of doing one Calorie of external work under these conditions was 3.3 Calories, or expressed in another way the net efficiency of energy expenditure during climbing was 30 per cent.

c. That at rates of energy production up to about 200 Cals./m²/hr. effective heat loss by sweating was constant and relatively small in amount (5-10 Cals./-

m²/hr.) but that at higher levels of production the heat loss through sweating was proportional to the rise above 200 Cals./m²/hr. and was the most important means of adjusting heat loss.

d. That the combined avenues of convection and radiation (H_{cl}) were at all levels of energy production quantitatively the most important for energy loss and that total loss by these avenues increased sharply until energy production reached about 200 Cals./m²/hr., then levelled off.

e. That balance of energy production and loss ($D = 0$) occurred only at a production level of about 250 Cals./m²/hr.; cooling and warming of the body mass were proportional respectively to the fall or rise in energy production from the level of 250 Cals./m²/hr., or

$$\text{for G. S.: } D = 0.15 (250 - M) \quad \text{for J. S.: } D = 0.20 (250 - M)$$

Under these particular experimental conditions the mode of adjustment of energy loss to production was markedly different over the low and high ranges of

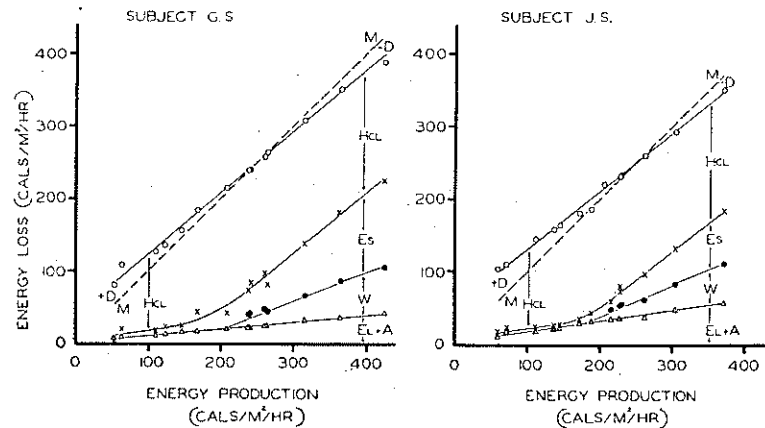


Fig. 1. Part played by various avenues of energy loss at several rates of metabolic energy production. For key to symbols see text.

energy production. Below about 200 Cals./m²/hr. changes in energy loss by the combination of convection and radiation were most important, whereas at higher energy production levels sweating and external work were most important (table 3).

It is pure coincidence that thermal sweating (as evidenced by rise in E_s values above the base value of 5-10 Cals./m²/hr. indicative of insensible perspiration) and external work both first appeared when energy production rose above about 200 Cals./m²/hr. Had no climbing been done at levels of energy production higher than 200 Cals./m²/hr., we believe that E_s would have approximated the value of $E_s + W$ in these experiments. Evidence suggesting that this would be so is presented in table 4, which gives the results of level walking experiments in which energy expenditure was about 260 Cals./m²/hr.

It also seems likely that in downhill walking E_s would have been reduced by an amount equivalent to the negative work of descent.

Effects of activity on the insulation value of clothing. The resistance provided by the clothing against heat losses by convection and radiation, i.e., the Clo value, was more than twice as great when the subjects sat or stood quietly as when they walked moderately fast (table 1).⁵ When insulation was plotted as a function of the speed of level progression (fig. 2) incorporating results of additional walking experiments at 4.5 miles per hour and a running experi-

TABLE 3
Part played by factors in adjusting energy loss to energy production
(Average of data on both subjects)*

FACTOR	WITH ENERGY PRODUCTION BELOW 200 CALS./M ² /HR.	WITH ENERGY PRODUCTION ABOVE 200 CALS./M ² /HR.
Convection and radiation (H_{cl}).....	71%	10%
Sweating (E_s).....	16	41
External work (W).....	0	36
Respiration ($E_r + A$).....	13	13
	100%	100%

* Percentage by which the total energy losses were excessive, i.e., caused accumulation of body heat debt, at energy production levels below 250 Cals./m²/hr., is represented by

$$\frac{0.18(250 - M)}{M} \times 100;$$

percentage by which energy losses were deficient above 250 Cals./m²/hr. is given by the same expression.

TABLE 4
Comparison of energy losses by evaporation of sweat (E_s) and work (W) in level and uphill walking experiments which involved similar energy expenditure

SUBJECT	SPEED	GRADE	M	E_s	W	$E_s + W$
	m.p.h.	%				
G. S.	4.5	0.0	261	58	0	58
G. S.	3.5	4.5	260	49	24	73
J. S.	4.5	0.0	261	63	0	63
J. S.	3.5	4.5	262	35	25	60

ment at 6.0 miles per hour it was found that the regression of insulation with speed takes the form of a curve. Starting at about 2.7 Clos when standing, and initially steep, this curve flattens out at 1.2 to 1.3 Clos when speed is 4 miles

⁵ Example to show method of calculation using equation (1); when subject G. S. was sitting quietly $I_{clo} = \frac{3.09(87-0)}{77} - 0.4 = 3.1$. The value 87°F. was used for T_s because it lies midway between 90°F., the assumed initial mean skin temperature, and 84°F., the measured final skin temperature; 0.4 is the insulation of the air with the 2-mile per hour turbulent wind that blows in our cold room (cf. Burton, 1945b for discussion of effects of wind and temperature on I_a).

per hour or greater. Although it frequently had been observed that any shift in the position of the body when clothing or sleeping bags were worn in the cold room caused subjects to feel colder, it had not been anticipated that systematic body movements could decrease the effective insulation of clothing to less than half of the value when quiet.

This decrease in effective insulation was so large that reinspection of the values for factors in the heat balance equation seemed desirable. Of the factors determining the value of H_{cl} in the equation the only one seriously contestable is E_s , which was derived from the calculated value for net effective sweat using the method described by Belding et al. (1947). What if all the sweat secreted in these experiments were efficient for skin cooling (actually an impossibly favorable situation since so much remained in the clothing)? Then, in a sample case, when G. S. walked at 3.5 miles per hour on the level the insulation value

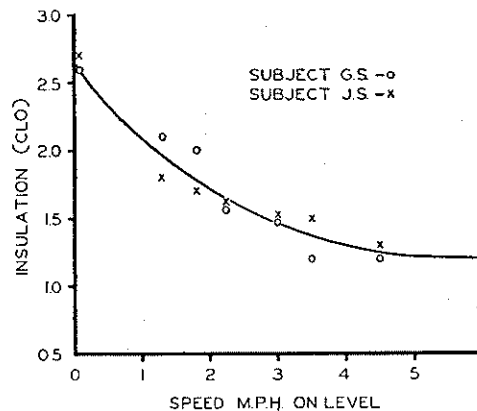


Fig. 2. Insulation provided by Arctic Uniform as a function of speed of forward progression.

would have been calculated as 1.4 Clos instead of the 1.2 Clos arrived at when E_s was calculated in the way that we have recommended; it is clear that no manipulation of the value for E_s could possibly raise the insulation value of the clothing in this walking experiment to the value obtained when the man was not exercising. Further calculations show that had the insulation remained at the large value found during quiet standing (2.7 Clos) the subject would have had to sweat over 600 grams in two hours to maintain the same thermal balance even if every gram had been 100 per cent effective for skin cooling; sweating would have had to exceed 1200 grams with the net sweating efficiency which we believe would have been applicable. Yet actually the man only sweated 253 grams in this experiment. The fact that I_{clo} was 1.2 instead of 2.7 during this walk not only meant a predicted saving of sweat of about 1000 grams in two hours, but also meant that the subject was comfortable instead of excessively warm in this clothing while performing this task. The situation is qualitatively similar for J. S. under the same walking conditions, and for other walking experiments on both subjects. It must be concluded, then, not only that the insulation of this

clothing was reduced during activity, but also that this reduction was appropriate in that it greatly reduced the requirement for sweating.

It would be interesting to learn whether increased radiation or increased convection was responsible for the extra transfer of heat during activity. Potential heat exchanges between the skin and environment were, of course, reduced enormously by the presence of clothing. If no clothing had been worn and skin temperature had been maintained at 85°F. calculations made using constants suggested by Burton (1945b) show that combined losses by radiation and convection would have approximated 650 Cals./m²/hr., of which about one-fifth would have been lost by radiation. This may be compared with the actual loss by these combined avenues of about 85 Cals./m²/hr. in the sitting and standing experiments and of up to 170 Cals./m²/hr. in the walking experiments. Thus it is fair to say that the clothing blocked about 74 to 87 per cent of potential heat loss by radiation and convection.

TABLE 5

	MEAN TEMP. OF SKIN	MEAN TEMP. OF SURFACE OF CLOTHING	GRADIENT
	°F.	°F.	°F.
Sitting quietly.....	84	7	77
Walking at 3.5 m.p.h. up a 6.5 per cent grade.....	89	14	75

Unfortunately it was not feasible to separate the effects of the clothing on losses by radiation and convection. Burton (1943) found that heat loss through kapok-filled air spaces was about 15 per cent greater when the spaces were bounded by plates with blackened inner surfaces than when they were bounded by plates with polished inner reflecting surfaces. This may be taken as an indication that at least 15 per cent of the heat loss through our clothing was by radiation. In attempting explanation of the difference in resistance to heat flow during walking and resting it would seem reasonable to suppose that convective losses were more influenced than radiation losses because such radiation as occurred from layer to layer would presumably be affected only by a changed gradient of temperature through the items of clothing. That such a change in gradient was small and in a direction to decrease transfer by radiation is indicated by the average skin temperatures and surface temperatures of the clothing in sitting and walking experiments (table 5). The latter were obtained both with a radiometer and with thermocouples.

It is relatively easy to see how increased convection losses might occur during walking experiments *a*, as a result of actual infiltration of cold air into the clothing at the garment openings or through the outer windbreak fabrics, or *b*, as a result of mixing the air trapped under the windbreak garments. However, it is not necessary to use the first explanation because when an air-impermeable outer covering (sealed carefully at the ankles, wrists, waist and margins of the face) was substituted for the usual windbreak outer garments effective insulation

during walking fell off fully as much (table 6). In these experiments the subjects walked at 3.5 miles per hour up a 6.5 per cent grade.

With infiltration of air into the clothing ruled out as an explanation for the decrease in effective insulation during walking we turn to an examination of the clothing to determine whether it is reasonable that mixing of air within the clothing should result in a twofold or greater variability in transfer of heat at the same temperature gradient. Certain unpublished data of Paul Siple and his co-workers of the Research and Development Branch, Office of the Quartermaster General, are useful here. These workers measured the actual thickness of the individual garments making up the Arctic Uniform and then determined the girth of wearers as successive layers of the clothing were added over the body. They found that the average total thickness of the fabrics was only about 0.38 inch, but that the total thickness when they were worn on the body averaged about 1.12 inches. The air spaces between the layers must then have had a total thickness of about 0.74 inch. If we assume that these values applied for our subjects what insulation did the fabrics and the air spaces between them provide

TABLE 6

CLOTHING	SUBJECT C. S.		SUBJECT J. S.	
	No. exps.	I_{clo}	No. exps.	I_{clo}
Arctic Uniform; regular windbreaks...	7	1.2	7	1.3
Arctic Uniform; air-impermeable windbreaks.....	2	1.1	2	1.1

when our subjects sat and stood quietly? When thermal conductivity apparatus has been used with fabrics of moderate density, such as pile fabrics, it has been found (cf. Burton, 1943; also Speakman and Chamberlain, 1930) that the insulation provided by new, clean garments a , was essentially proportional to thickness, b , depended very little on the material or weave used, and c , was about the same as the insulation provided by dead air (about 4.7 Clos per inch). With fabrics of greater density insulation declined somewhat and was greater for wool than for cotton fibres. For this Arctic clothing it seemed fair to figure the fabric insulation at 4.5 Clos per inch, which gave about 1.7 Clos for the thickness of 0.38 inch.

The data of Burton (1943) are also helpful for calculation of the insulation available from the air between fabric layers. He found that air trapped between two stationary, horizontal plates provided 0.31 Clo for the first 0.1 inch of thickness, 0.24 for the second, and 0.11 for the third, and that after thickness reached 0.4 inch the insulation rose no further but totalled about 0.72 Clo. This information was used to calculate the insulation provided by each of the spaces between the garments of our Arctic Uniform. On this basis it was predicted that the total insulation of these air spaces was about 1.4 Clos when the men were not moving, giving a predicted total insulation under these conditions of $1.7 + 1.4 = 3.1$ Clos. (This value does not include I_a , the insulation provided

by the relatively inert layer of air against the outside of the outer layer of clothing.)

We can only speculate concerning the effects of forced circulation of the air in the clothing due to frequent and ample body movements. A clue to the effect on insulation of the air trapped in the layers may be gained from the known effects of air movement on I_a . I_a is a curvilinear function of wind velocity (Burton, 1945 b) falling sharply from about 0.8 Clo when air movement is equivalent to a straight wind of 35 ft. per minute to 0.1 Clo at very high wind velocities. Since this insulation would theoretically be applicable at each side of each air layer reduction in insulation could be only to 0.2 Clo per space or from an average maximum of 1.4 Clo when a subject was quiet to a minimum of about 0.5 Clo during movement. This alone would result in a reduction of total insulation from 3.1 to 2.2 Clo. However, there is no reason to believe that circulation of air within the garments would be restricted to channels between the garments. The fabrics, except for those in the windbreak items, have a relatively high air permeability, and body movements may well pump air back and forth through them in an amount sufficient to reduce markedly the insulation which they provide.

Use of a heated cylinder to show effects of movement on insulation. Because of the indirect methods used in computing these insulation values of clothing from data obtained on men it was decided to check the finding that movement causes a decrease in insulation value of Arctic clothing by making direct determinations on a physical model. Accordingly a thermal conductivity apparatus was constructed in the form of a heated cylinder with dimensions approximating those of a human arm. This cylinder could be driven back and forth to simulate the movements of an arm during walking.

The cylinder was 3.5 inches in diameter and consisted of three separately heated parts, a central or test section 12 inches long, and two end sections 4 inches long which were used as thermal guard rings. A constant surface temperature (92°F.) was maintained on the test section by a Thermistor Electronic Thermoregulator. (This cylinder was similar in many respects to a stationary cylinder designed by the Climatic Research Laboratory of the Office of the Quartermaster General; the thermoregulator was furnished by courtesy of that laboratory.) A watt-hour-meter was used to measure the heat put into the test section to maintain this surface temperature. During operation no heat passed through the ends of the test section because both end (guard ring) sections were maintained at the internal temperature of the test section by carefully adjusting the heat to each guard ring with Variac transformers. Four thermocouples on the partitions between the sections indicated when heat was needed in the guard rings, and the temperature of the cylinder surface was measured at five locations by other thermocouples. Movement was accomplished by suspending the cylinder on the side of a 5.0 inch vertical disc which could be turned at various frequencies. When in motion the top of the cylinder described the circumference of the vertical disc, while the bottom either swung freely, or else was restricted to set amplitudes by the use of padded rings of various sizes.

Sleeves were cut from garments of the Arctic Uniform, drawn over the cylinder and bound tightly to the top guard ring. The fit of the four sleeves (from the underwear, shirt, pile parka and cotton windbreak parka) resembled that of the same clothing on a human arm in that the underwear fitted fairly snugly whereas

the other garments hung loosely with obvious air spaces between layers. Three sets of experiments were conducted, the results of which are summarized in table 7.

The results indicate that nearly as great reductions in insulation are obtainable by moving the model as were observed when men were walking rapidly or running, and that this is true even when infiltration of room air into the garments is prevented.

The measurements made on this heated cylinder seem to confirm the finding on men that the thermal insulation provided by an Arctic Uniform is markedly diminished during movement even though the absolute values obtained on the cylinder do not correspond with those found with the whole uniform on men.

When the fit of garments on the cylinder was tight no such decrease in insulation as a result of motion was observed.

TABLE 7

Insulation values obtained with sleeves of Arctic Uniform worn over movable copper cylinder

ARRANGEMENT OF CLOTHING ON CYLINDER	INSULATION(Clo)		
	Cylinder still	Cylinder moving*	Reduction in insul- ation due to moving
Sleeves of regular garments of Arctic Uniform; bottom of sleeves unbound.....	1.7	0.9	47%
Sleeves of regular garments of Arctic Uniform; bottom of windbreak sleeve bound to bottom of cylinder.....	1.9	1.2	37%
Sleeves of inner regular garments of Arctic Uniform; outer sleeve made of rubber dam (air-impermeable) and bound to bottom of cylinder.....	2.1	1.3	38%

* At 62 cycles per minute, the approximate frequency of arm movement when walking at 3.5 miles per hour; higher Clo values were obtained with lesser amplitudes of movement.

Prediction of conditions under which the Arctic Uniform will be adequate. When the insulation value of clothing is known it is possible to predict what environmental temperature will be comfortable at various levels of activity. The relation between ambient temperature for comfort and thermal insulation may be approximately expressed as:

$$T_a = \frac{3.09T_s - (I_{clo} + I_a)(0.75M)}{3.09} \quad (3)$$

Values for T_s , I_{clo} , I_a and M with this Arctic Uniform were assigned on the basis of the following considerations. It has been our experience that the mean skin temperature for comfort in the open does not vary greatly with activity, and may be as low as 90°F.; accordingly 90°F. may be used for T_s . I_a may reasonably vary between 0.2 and 0.6 Clo in the open; we select the value of 0.4, which is applicable for a 1.8 to 3.5 miles per hour wind and for our cold room. The average

energy production of the two subjects for each speed of level progression is obtained from table 1, and the average I_{clo} value at each speed from figure 2. The expression $0.75M$ is used to approximate the heat losses by radiation and convection (H_{cl}); the assumption is that $E_l + A + E_s$ was 25 per cent of M ; this is reasonable on the basis of the data on distribution of heat losses in experiments in which our men were comfortable; it also agrees closely with the findings for evaporative heat loss from resting subjects in a comfortable environment (Gephart and DuBois, 1916).

On the basis of these assumptions it is now possible to predict the air temperature for comfort while engaged in various activities. Results of such predictions are plotted in figure 3. The consensus of several subjects regarding comfort at various activities and environmental temperatures in about 100

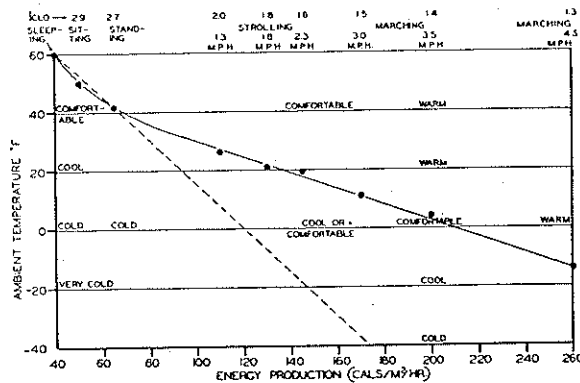


Fig. 3. Ambient temperatures for prolonged comfort in the Arctic Uniform at various activities. Solid line predicts conditions for prolonged comfort on the basis of our data on the insulation provided at various activities. (This insulation is indicated along the top of the figure.) Consensus of actual experience of subjects in two-hour exposures is also given where available. The broken line predicts the conditions for comfort if insulation remained 2.7 Clo regardless of activity. Wind = 2.5 miles per hour.

two-hour exposures in this uniform has been superimposed on this figure, and is found to agree well with the predictions. The range of temperatures within which a man was comfortable for this length of time while performing one activity was apparently somewhere between 20° and 40°F. The range of energy production (during level progression) over which comfort was observed was from 70 to 100 Cals./m²/hr. at any one environmental temperature.

The curve predicting comfort conditions in figure 3 would be displaced toward colder ambients if sunshine were present (cf. Blum, 1945, and Siple, 1945, for estimates of its effect). We would expect it to be displaced toward warmer ambients if part of the energy were expended in external work such as mountain climbing because another avenue of energy loss would be added. On the other hand, when walking down a mountain we would expect it to be displaced toward colder ambients.

The fact that effective insulation decreases when the intensity of activity in-

creases is of practical consequence. It means *a*, that maximum protection is provided when most needed, i.e., when men are idle. It also means *b*, that the range of activities within which a given assembly will provide comfort is larger. For example, in two-hour exposures men were actually comfortable at 40°F. when sitting quietly or when strolling at 2.3 miles per hour, activities involving energy production between 50 and 150 Cals./m²/hr., while at 0°F. the men were comfortable while walking at 2.3 miles per hour and at 3.5 miles per hour, activities involving energy production between 150 and 220 Cals./m²/hr. If the insulation had been 2.7 Clo at all activity levels the curve showing ambient temperature for comfort as a function of energy production would have been a straight line with a slope so much steeper (see the broken line in fig. 3) that the range of energy production within which comfort could be expected at any one ambient temperature would have been reduced to about half what it actually was, i.e., to between 35 and 50 Cals./m²/hr.

TABLE 8

Predicted requirements for insulation from clothing under conditions of shade and a 2½-mile per hour wind at 3 ambient temperatures

Actual protection provided by the Arctic Uniform is given; where protection requirements are within 25 per cent of actual protection provided by the Arctic Uniform they appear in italics.

ACTIVITY	<i>M</i>	+40°F.	0°F.	-40°F.	ACTUAL <i>I_{clo}</i> OF ARCTIC UNIFORM
Sitting.....	50	3.7	7.0	10.3	2.9
Standing.....	60	3.0	5.8	8.5	2.7
Strolling 2.25 m.p.h.....	145	1.0	2.2	3.3	1.6
Level walking 3.5 m.p.h.....	200	0.6	1.5	2.3	1.4
Walking 3.5 m.p.h. up 6.5% grade.....	300	0.4	1.1	1.7	1.3
Level walking 4.5 m.p.h.....	260	0.4	1.0	1.7	1.3

Perhaps clothing could be developed the insulation of which would vary to such an extent that the same clothing would be proper at one environmental temperature whether a man was seated, standing quietly or walking at a brisk pace. Table 8 shows what the insulation should be to provide comfort for men engaged in several different activities at any one of three environmental temperatures. Assumptions were those made in preparation of figure 2 except that where *W* was applicable it was subtracted from 0.75 *M*. Assuming that it would be desirable, how close could we come to providing a uniform which would be reasonably adequate at 40°F. regardless of activity? The present Arctic Uniform would be satisfactory while sitting or standing, but would offer far too much protection if worn buttoned up during hard work. Possibly if all four garments covering the trunk could be opened down the front insulation provided would be reduced to the required 0.4 Clo, but it would be cumbersome to wear this large bulk of clothing unless most of a man's time was being spent quietly, e.g., in a foxhole. At 0°F. the bulk required for protection during sitting and

standing is such that freedom of movement would be hampered. Actually the warmest clothing that we have ever studied provided only about 5 Clos of protection; this means that at below zero temperatures a man must be active most of the time to avoid becoming cold even when wearing the warmest clothing (at night he will be fortunate if he has a sleeping bag that provides 10 Clos of protection). If it were possible to fabricate a clothing assembly which would provide the protection necessary at various activities at one ambient temperature this characteristic should be partially under control of the wearer, that is, it should involve buttoning or some such control. Otherwise if a man found himself in a climate too cold for his clothing he could not warm himself up by exercising, but would have to resort to means of raising energy production which did not increase frequency or amplitude of movement, such as voluntary shivering or isometric contraction of large muscle groups.

Presumably the reason for specifying several separate, relatively thin, loosely fitting items for this Arctic Uniform rather than one or two thick items was to furnish one set of garments that could be used selectively in securing necessary protection while soldiers were engaged in various activities over a wide range of environmental temperatures. These studies of physiological responses have served to indicate additional virtues of this uniform which were perhaps not wholly appreciated by the Arctic experts who helped design it. One was that the complete assembly gave considerably greater warmth for its weight during rest because of the presence of several layers of relatively inert air between the garments. Another was that because such a large part of the potential protection of the assembly depended on insulation provided by inert air between garments the insulation was reduced markedly when body movements "pumped" this air back and forth during exercise. Such a decrease in effective insulation during exercise is considered a desirable feature of any clothing assembly because it extends the usefulness over a broader range of activities at any one ambient temperature, and because it reduces the amount of sweating necessary to eliminate the heat produced at high levels of activity.

SUMMARY AND CONCLUSIONS

1. Two subjects have been exposed at 0°F. while dressed in an Arctic Uniform and while engaged in controlled activities involving a wide range of energy production. Measurements were made of oxygen consumption, pulmonary ventilation, body weight loss, moisture uptake of the clothing, and rectal and skin temperatures. The results were used in calculating heat production, body heat debt, sweating, effective heat loss by sweating, evaporative heat loss from the lungs, heat loss from the lungs in warming the air, external work, heat loss through the clothing, and insulation value of the clothing.

2. Activities consisted of sitting, standing and walking at various speeds on the level and uphill. In the lower range of activities (50-70 Cals./m²/hr.) the men were cold, in the upper they were hot (energy production 300 to 500 Cals./m²/hr.). Under these environmental conditions the principal mode of adjustment of energy loss at energy production levels below 200 Cals./m²/hr.

was by modification of convection and radiation losses through the clothing, whereas at higher levels of production, sweating, or sweating and external work were the most important. Heat expended as a result of sweating during level walking about equalled the sum of energy expended in external work and in evaporation of sweat when walking uphill (at a slower speed) with the same energy production.

3. Energy losses exactly equalled energy production only at a metabolic level of about 250 Cals./m²/hr. At lower production levels mean body temperature fell and at higher ones it rose.

4. One subject who averaged 36 per cent less volume of respiration than the other at the same level of activity, and had correspondingly smaller heat losses from the lungs, sweated enough more than the other subject to compensate for his smaller heat loss in breathing. Since these two subjects had quite similar energy production (per unit surface area), body heat debt, skin temperature, and rectal temperature, it was concluded that the "settings" of the temperature regulating centers of these two men when engaging in similar activities were quite similar.

5. The insulation provided by the clothing was a curvilinear function of speed of level progression, was 2.7 Clos when the subjects were standing quietly, 1.6 when walking at 2.25 miles per hour, and 1.2 when running at 6 miles per hour. Convection currents set up between the layers of clothing and through the relatively air-permeable garments lying under the windbreak layer were held to be responsible for this decrease in insulation.

6. Predictions were made concerning the ambient temperatures for comfort in this uniform at various grades of activity and were shown to agree with experience of a number of subjects. Consideration was also given to the desirability and possibility of designing clothing which would maintain comfort at some one temperature regardless of activity.

Acknowledgments. We are indebted to the Quartermaster Corps, U. S. Army, for the services of Sgts. G. Selden, S. Camitta, R. Williams, E. Ainsworth and C. Ethier, and Cpls. J. Stachelek, P. Koby, J. Eichar and F. McVay who acted as subjects and technicians in these experiments. Mr. W. O. Holmes also provided valuable technical assistance.

REFERENCES

- BELDING, H. S., R. C. DARLING, D. R. GRIFFIN, S. ROBINSON AND E. S. TURRELL. In Clothing test methods. Ed. L. H. Newburgh and M. Harris Nat. Res. Council, Comm. Av. Med. Report No. 390: 9, 1945.
- BELDING, H. S., H. D. RUSSELL, R. C. DARLING AND G. E. FOLK. This Journal 149: 204, 1947.
- BLUM, H. F. In Clothing test methods. Ed. L. H. Newburgh and M. Harris Nat. Res. Council, Comm. Av. Med. Report No. 390: 23, 1945.
- BURTON, A. C. Report to Ass. Comm. Av. Med. Res. No. C 2035 to Nat. Res. Council. Can. August 11, 1941.
- Report to Ass. Comm. Av. Med. Res. No. C 2464 to Nat. Res. Council. Can. April 2, 1943.
- In Clothing test methods. Ed. L. H. Newburgh and M. Harris, Nat. Res. Council, Comm. Av. Med. Report No. 390: 5, 1945; Ibid. 390: 37, 1945.

- CHRISTIE, R. V. AND A. L. LOOMIS. *J. Physiol.* **77**: 35, 1933.
- GAGGE, A. P., C.-E.A. WINSLOW AND L. P. HERRINGTON. *This Journal* **124**: 30, 1938.
- GAGGE, A. P., A. C. BURTON AND H. C. BAZETT. *Science* **94**: 428, 1941.
- GEPHART, F. C. AND E. F. DuBOIS. *Arch. Int. Med.* **17**: 902, 1916.
- HOUGHTEN, F. C., W. W. TEAGUE, W. E. MILLER AND W. P. YANT. *Trans. Am. Soc. Heat. Vent. Eng.* **35**: 345, 1929.
- SIPLE, P. A. *Proc. Am. Phil. Soc.* **89**: 200, 1945.
- SPEAKMAN, J. B. AND N. H. CHAMBERLAIN. *Trans. J. Text. Inst.* **21**: 29, 1930.
- WINSLOW, C.-E.A., L. P. HERRINGTON AND A. P. GAGGE. *This Journal* **124**: 51, 1938; *Ibid.* **124**: 692, 1938.
- WINSLOW, C.-E. A., A. P. GAGGE AND L. P. HERRINGTON. *This Journal* **127**: 505, 1939.
- YAGLOU, C. P. *J. Ind. Hyg.* **9**: 297, 1927.
- YAGLOU, C. P. AND A. MESSER. *J. A. M. A.* **117**: 1261, 1941.